Modal choice in a TIMES model

Report submitted to IEA-ETSAP, May 2012

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Summary

Climate change mitigation clearly requires a focus on transport that should include improved representation of travel behavior change in addition to increased vehicle efficiency and low-carbon fuels. Most available energy/ economy/ environment modelling tools focus however on technology and fuel switching and tend to poorly incorporate travel behavior. The objective of this research project was to incorporate modal choice within passenger transport in a TIMES model, which to date has been exogenously modelled, so that no competition exists between alternative modes. This report introduces a novel approach to modelling modal choice in TIMES.

In typical TIMES models, individual modal travel demand is exogenously defined over the model time horizon and while technologies can compete within modes on the basis of cost (fuel costs, investment costs and O&M costs), there is no competition between modes. We built a simple illustrative TIMES model, in which future overall travel demand is exogenously defined but not specified by individual mode. We allowed competition between modes and imposed a constraint on overall travel time in the system. This constraint represents the empirically observed travel time budget (TTB) of individuals, constraining the model choosing between between faster and more expensive modes (e.g. cars) and slower but cheaper mode (e.g. buses or rail). Transport studies suggest that people spend, on average, a fixed amount of their daily time budget on travel irrespective of income or location. We further introduced a new variable, called travel time investment (TTI), which acts as a proxy for infrastructure investments (for example, new bus services or rail lines) to reduce the time associated with travel.

We populated the model with data from California, US and from Ireland and generated results to 2020 for a reference scenario, an investments scenario and a CO2 emissions reduction scenario. The results show the significance of modal shifting in the CO2 mitigation scenario.

1 Introduction

1.1 Background

Transportation contributes to 23% of energy-related CO_2 emissions globally. With increasing demands especially for light-duty vehicles, freight, and aviation, global transport CO_2 emissions are expected to double by 2050 (IEA 2011). Reducing greenhouse gas emissions from the transport sector will require complementary policies in improving the efficiency of vehicles, introducing low-carbon fuels and advanced vehicles technologies, and better travel demand management (Schäfer, Heywood et al. 2009; Skinner, Essen et al. 2010). Most of the growth in demand for cars will come from developing countries, as car travel in developed countries essentially saturated, and is projected to remain flat in the next few decades (IEA 2010). On the other hand, public transit and aviation already play an important role in many developed (especially Europe) and developing countries (Figure 1). The importance of their role is expected to continue to increase given the need to drastically reduce on-road transportation emissions in order to meet stringent climate targets (Figure 1) (Fulton, Cazzol et al. 2009; IEA 2010).

However, while most of the integrated assessment (IA) models that governments rely on for developing climate mitigation policies have been able to project portfolios of advanced fuels and vehicle technologies given climate goals, most of these models are ill suited to examine potential travel demand changes and travel mode shifts given climate policies and changes in fuel prices, and most importantly the necessary investments needed to reduce vehicle travel, increase public transit shares, and non-vehicle infrastructure given climate goals (Schäfer 2012). Most IA models use scenario describing future travel mode shifts without explicitly linking demand changes to drivers (e.g. fuel price changes) or infrastructure and technology investment decisions. This is evident in Figure 1 and other studies (Fulton, Cazzol et al. 2009; IEA 2010; Skinner, Essen et al. 2010).

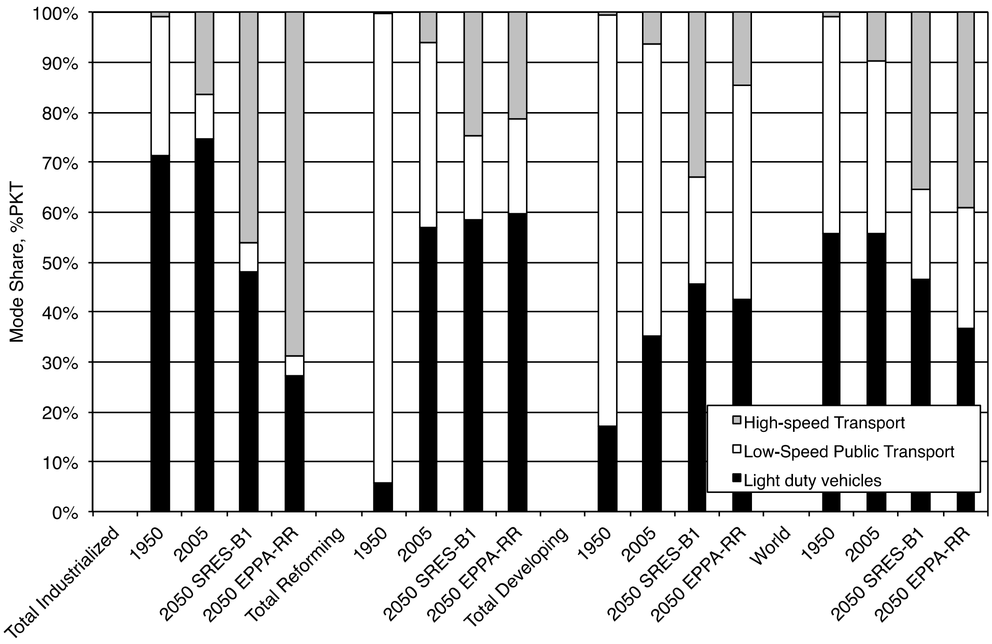

Figure 1: Relative share of transport modes in the three metaregions and the world, in history (1950 and 2005) and in projections (2050) based on various scenarios. SRES-B1: Special Report on Emissions Scenarios – SRES, rapid economic growth and advanced technology scenario. EPPA-RR: MIT Emissions Prediction and Policy Analysis (EPPA) CGE model. Source: (Schäfer, Heywood et al. 2009).

A recent seminal paper by Schäfer (2012) provides a critical review of the (lack of) modelling of behavioral changes in transportation in energy/economy/environment (3E) models, compares common methodologies employed in IA models, their shortcomings and gives recommendations for future improvement. This paper states that "Overall, introducing behavioral change in transportation into E3 models is feasible and intellectually rewarding. However, when pursuing holistic approaches to mitigating energy use and emissions, it is indispensable." Our paper explores some of the recommended methologies and applies them for the first time in a bottom-up optimization modeling framework using the TIMES model and implements this in two case study based on the Californian TIMES model and the Irish TIMES model.

We will describe the TIMES modeling framework and review the role of transport in energy models and key underlying concepts of travel behaviors in Section 1.2, describe our methodology in Section 2, compare data and describe sources of the case studies in Section 3, present results in Section 4 and conclude in Section 5.

1.2 Transport in energy systems models

Transport modelling is a very well established discipline used widely by decision-makers for planning infrastructure such as airports, roads and railways, for cost-benefit analyses, and environmental impact assessments. Transport planning models typically simulate travel trips by origin and destination, trip purpose, mode of travel and household demographies. Mode choice computes the proportion of trips between each origin and destination is often modelled using by a logit type model (de Dios Ortúzar and Willumsen 2001). Behaviour is generally a strong element of these models, whereas there is generally very little or no treatment of energy demand.

On the other hand, Energy/Environment/Economy (E3) models explicitly look at the energy system to examine issues ranging from macroeconomic interactions to looking at pathways to meeting climate mitigation scenarios. Schäfer (2012) describes how transport is represented in a range of these models, in particular examining the role of behaviour in transport, which is necessarily more constrained in energy models.

The TIMES model, used to implement the approach described here, is a bottom-up energy systems model developed by the Energy Technology Systems Analysis Programme (ETSAP), an IEA Implementing Agreement (Ó Gallachóir et. al. 2012). Energy systems models like TIMES are generally partial equilibrium linear optimisation models, with very rich technological detail of the entire energy system, from fuel production and imports to energy conversion and demand technologies. The total system cost is minimised over a time horizon subject to user-defined constraints, such as maximum system-wide CO_2 emissions. Demands are generally exogenously projected, and can be derived from other models. A facility for elastic demand is available in TIMES, where end-use can be a function of price or income. Schäfer (2012) gives a number of examples of such models, none of which consider behaviour. Because technology selection in these models is determined by the least system cost, and travel behaviour is largely dictated by user costs, which can include time costs and barrier costs, it has been difficult to model realistic modal choice behaviour in these models. Mode choice is therefore typically exogenous, which is a significant limitation, given that this is considered to be an important step in moving towards sustainable mobility (Banister 2008).

Other types of E3 models include hybrid and top-down approaches, which, because the modelling approaches are not strictly linear optimisation, typically have more flexible and nuanced representations of travel demand, but not such a detailed representation of energy technologies as bottom-up models. The hybrid models include the Global Change Assessment Model (GCAM) model, developed at the Pacific Northwest National Laboratory, which is a general equilibrium model which solves for prices, supply and demand for all markets. Mode choice is modeled using a logit model approach, where the cost of time is included in the generalized cost for transport, and so increases in GDP leads to a demand for faster modes. The Canadian Integrated Modelling System (CIMS) also includes a logit sub-model for mode and fuel choice. A third hybrid model with transport behaviour is IMACLIM-R (IMpact Assessment of CLIMate policies-Recursive version), developed at CIRED, which maximizes a utility function subject to travel budget constraints. Infrastructure is endogenous: a decrease in supply leads to congestion and lower speeds, which feeds back into the model.

Constraining overall travel time in this latter model is the essence of the contribution of this paper to modelling travel behaviour in bottom-up energy systems models. It has been empirically observed that the average daily travel time is constant across many different populations (Marchetti 1994) (Gakenheimer 1999). Figure 2 shows results from the UK National Travel Survey (NTS) on travel patterns since 1970. It shows that while total travel distance has grown by approximately 60% in the period, total annual travel time per person has stayed constant. This has introduced the concept of a fixed travel time budget (TTB), which is invariant under policy and economics. Schäfer and Victor (2000) use this TTB of 1.1 hours per day along with a fixed travel money budget to project future levels of mobility and transport mode. This paper also follows this approach, which is consistent with the linear programming approach adopted.

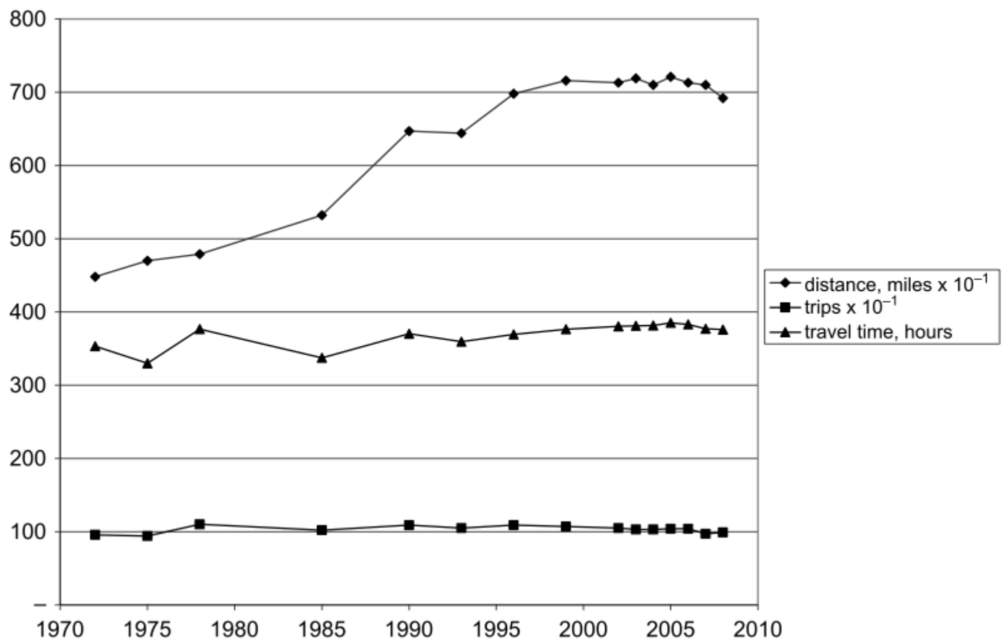

Figure 2: Travel time (hours per person per year), distance (miles pppy) and journeys (pppy) in the UK. Source: (Metz 2010)

2 Methodology

This section describes the basic model structure of the methodology and its implementation in a simple illustrative TIMES model. In this model, different transport modes compete on the basis of fuel and capital costs to deliver overall travel demand, while a constraint on overall travel time in the system, representing the travel time budget (TTB) of individuals, ensures that faster and more expensive modes can also compete. We introduce a new variable, travel time investment (TTI), a proxy for investments to reduce the time associated with travel. This model is then tested under a reference scenario (to 2020), an investment scenario and a CO_2 emissions reduction scenario.

2.1 Model structure

Motorised travel demand is represented by person miles travelled (PMT), which is the sum of demands of car (CMT), bus (BMT) and train (TMT). PMT for a technology is given by the vehicle miles travelled (VMT) multiplied by the load factor (LF, or occupancy of the vehicle). PMT is divided by long and short distance demand (PMT_L and PMT_S) in order to capture the characteristics of the different technologies servicing the different demands: High-speed train and buses can service long distance travel, while city buses can service short distance; cars serve both. Furthermore, the speed of technologies serving long and short distance differs significantly: For example, for longer distance a rail trips, the required waiting time is absorbed by the speed of the overall journey and is more significant in shorter trips.

The model is based on a least-cost linear programming approach. It determines $PMT_{t,d}$, the travel demand for long and short distance (d) of each of the technologies (t) such that the overall system cost is minimised. The cost of technology activity, $c_{t,d}$ is the cost in $/PMT of travel in each technology producing long or short distance travel demand d, given by the sum of the fuel, investment and O&M costs in dollars per PMT.

The model is constrained to meet annual short- and long-distance travel demand, which are modelled exogenously and can be based on the output of transport models, for example.

The concept of a travel time budget (TTB in million hours, mhs) is introduced to the model to represent the empirically observed fixed travel time per-capita in the real world, as described in Section 1. This enables competition between different transport modes based on travel time in addition to cost. Without this the model will be likely to switch modes immediately to the cheaper but slower and more time-costly public transit modes, which doesn’t reflect travel behaviour. Previous TIMES models in general have fixed travel demand for each mode, and while allow technologies to compete within modes, but not between modes.

Ideally, speed and infrastructure would be endogenous to the model, so that the model could invest into decreasing travel time. We introduce a variable *TTI* (travel time investment) which is a proxy to endogenise this relationship.

The model determines $PMT_{t,d}$ and $tti_{t,d}$ subject to:

Minimise $$C = \sum_{t,d} PMT_{t,d} \cdot c_{t,d}, \qquad \text{(Equation 1)}$$

where $PMT_{t,d}$ is the travel demand of technology t for long or short demand d and cost is the sum of fuel, investment, O&M and TTI cost:

$$c_{t,d} = f_{t,d} + i_{t,d} + om_{t,d} + tc_{t,d};\qquad \text{(Equation 2)}$$

where fuel cost $f_{t,d}$ is a product of the price per unit of energy of fuel and the energy intensity by technology, divided by the load factor:

$$f_{t,d} = (F \cdot int_{t,d}) \div LF;\qquad \text{(Equation 3)}$$

and the cost of travel time investment $tti_{t,d}$ depends on vehicle speed:

$$tc_{t,d} = (tti_{t,d} \div s_{t,d}) \cdot i\qquad \text{(Equation 4)}$$

where $s_{t,d}$ is the speed in miles per hour of technologies and i is the TTI cost;

The model is subject to the constraints:

$$\sum_{t} PMT_{t,d} = PMT_d \text{ for long and short demand } d\qquad \text{(Equation 5)}$$

and

$$\sum_{t,d} \left(\frac{PMT_{t,d}}{s_{t,d}} - tti_{t,d} \right) \le TTB\qquad \text{(Equation 6)}$$

We may also constrain the model to meet a CO_2 target X:

$$\sum_{t,d} PMT_{t,d} \cdot e_{t,d} \le X\qquad \text{(Equation 7)}$$

where $e_{t,d}$ is the emissions in gCO_2/PMT of each technology, which is given by the fuel emissions factor, technology efficiency and mode load factor.

2.2 TIMES Implementation

2.2.1 Transport Reference Energy System

In TIMES models the transport sector typically comprises a stock of technologies, in competition, that contribute to meet each exogenously defined modal travel demand (in passenger miles travelled–PMT or passenger kilometres travelled–PKT). Figure 3 shows an example of this approach in the form of Reference Energy System extracted from current Irish TIMES passenger transport sector (Ó Gallachóir et.al. 2012). An equivalent structure characterizes the CA-TIMES model.

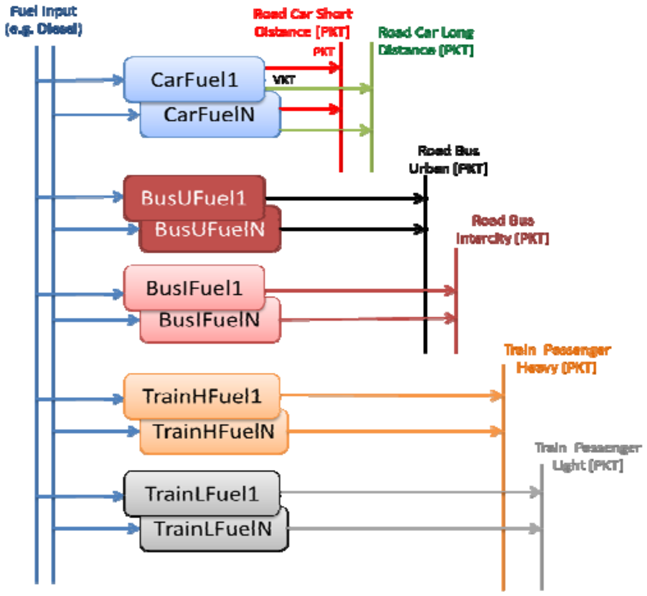

Figure 3 – Reference Energy System for Irish TIMES passenger travel sector. Here technologies can compete within modes but not between modes.

Within the new Reference Energy System, as shown in Figure 4, we introduce just two travel demand commodities: long distance demand (TLDD) and short distance demand (TSDD) expressed in PMT/year. In order to produce energy service demands all technologies such cars, trains and buses have two inputs: the fuel input and the time input. Here the TIME input describes the travel time from origin to destination, which is dependent on the modal speed, waiting and transfer time. This depends on technology, infrastructure, reliability, congestion, accessibility, etc. The Travel Time Budget (TTB) is exogenously defined in a similar way to demand growth. The model uses Travel Time Investment (TTI) as discussed in Section 2.1.

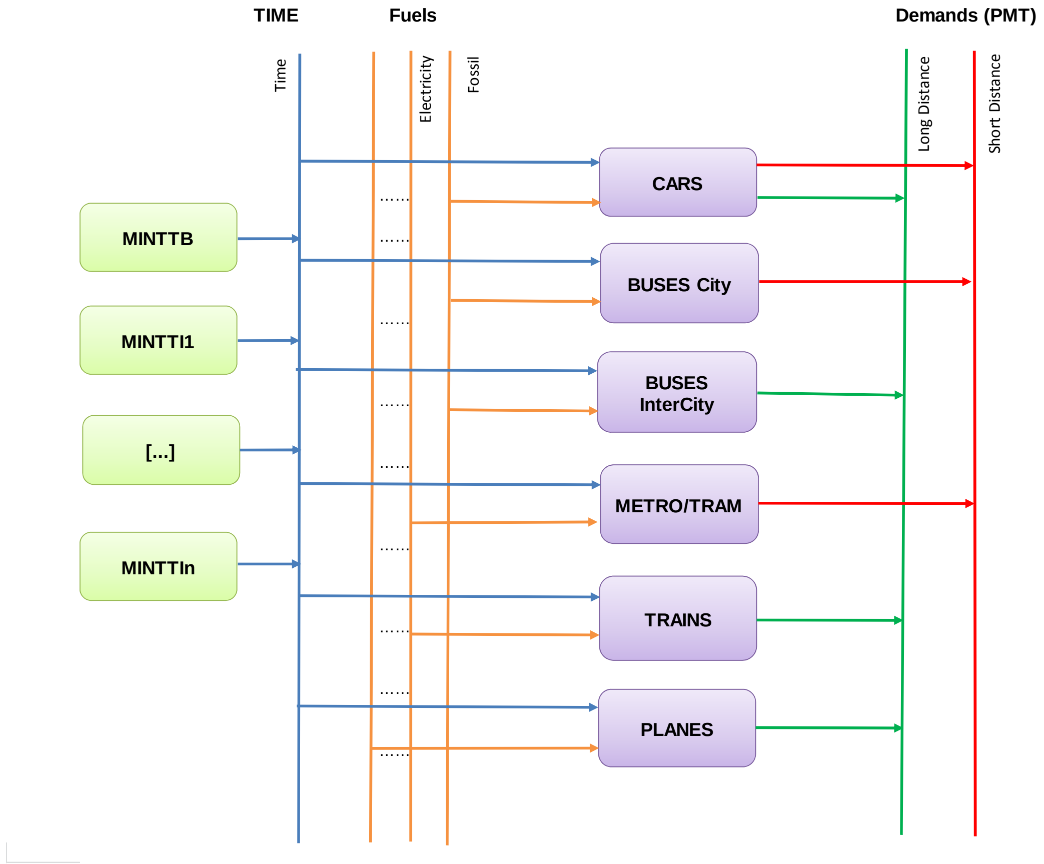

Figure 4 – Proposed Reference Energy System

2.2.3 How to implement the VEDA-TIMES model

The VEDA-TIMES model implementation includes commodity and process definitions as always. This model includes the following commodities, as shown in Figure 5:

- Fossil fuels (NRG type) in PJ;
- Travel TIME (NRG type) in Mhs (Million hours);
- Long and Short distance demand (DEM type) in PMT (Person Miles Travelled)
- Emissions of CO_2 (ENV type) in kton.

Commodities				
~FI_Comm				
Csets	**Region**	**CommName**	**CommDesc**	**Unit**
*Commodity Set Membership	Region Name	Commodity Name	Commodity Description	Unit
NRG		TRAOIL	Transport fossil fuels	PJ
		TRAELC	Transport electricity	PJ
DEM		TSDD	Transport Short Distance demand	PMT
		TLDD	Transport Long distance demand	PMT
ENV		TRACO2	Transport CO2	kt
NRG		TIME	Time commodity	Mhs

Figure 5 – Commodity definition

Within the new Reference Energy System, as shown in Figure 4, we introduce just two travel demand commodities: long distance demand (TLDD) and short distance demand (TSDD) expressed in PMT/year. In order to produce energy service demands all technologies such cars, trains and buses have two inputs: the fuel input and the time input. Here the TIME input describes the travel time from origin to destination, which is dependent on the modal speed, waiting and transfer time.

The TIME input is produced by TTB and TTI mining processes at different prices. The TIME commodity availability is the sum of MINTTB output and MINTTIn outputs.

The model includes the following existing technologies, as shown in Figure 6:

- Demand technologies (DMD)
    - Cars (short and long distance); the same car can produce both short and long distance demand but this is simulated in the model with a trick. There are two different technologies, TCARS for short and TCARL for long distance. This is necessary to implement in the model different TIME input for short and long distance.
    - Buses (short and long distance); there are two different buses and they can produce short (City) or long (Intercity) distance demand.
    - Trains (short and long distance); there are two different trains and they can produce short (City) or long (Intercity) distance demand.
    - Transport aviation for long distance demand.

Processes				
~FI_Process				
Sets	**TechName**	**TechDesc**	**Tact**	**Tcap**
*Process Set Membership	Technology Name	Technology Description	Activity Unit	Capacity Unit
DMD	TCARS1	Transport short distance car 1	PMT	000_units
	TCARL1	Transport long distance car 1	PMT	000_units
	TBUSS1	Transport City Bus short distance 1	PMT	000_units
	TBUSL1	Transport Intercity Bus long distance 1	PMT	000_units
	TTRAINS1	Transport City Train short distance 1	PMT	000_units
	TTRAINL1	Transport Intercity Train long distance 1	PMT	000_units
	TPLANEL1	Transport Aviation 1 long distance	PMT	000_units
MIN	MINTRAOIL	Transport fossil fuels Infrastructure	PJ	
	MINTRAELC	Transport electricity Infrastructure	PJ	
	MINTTB	Travel TIME budget availability	Mhs	
	MINTTI1	Travel TIME Investment availability 1	Mhs	
	MINTTI2	Travel TIME Investment availability 2	Mhs	
	MINTTI3	Travel TIME Investment availability 3	Mhs	
	MINTTI4	Travel TIME Investment availability 4	Mhs	

Figure 6 – Process definition

- Mining technologies for fuels and TIME availability (MIN). Figure 7 show how the mining technologies are described in the model.
  - Oil mining (MINTRAOIL) to generate transport oil availability in the model;
  - Electricity mining (MINTRAELC) to generate transport electricity availability in the model;
  - TTB mining technology for TTB availability in the model. The process output is TIME and the activity is bounded in the base year template and then updated via scenario file.
  - TTI mining technologies for TTI availability and costs in the model. The processes output is TIME and the activity of each process is bounded in the base year template and updated via scenario file. The same happens for the related costs.

	~FI_T		
TechName	**Comm-OUT**	**COST**	
*Technology Name	Output Commodity	Commodity Cost	
*Unit		M$/PJ	
MINTRAOIL	TRAOIL	10.4	
MINTRAELC	TRAELC	22	
	~FI_T		
TechName	**Comm-OUT**	**COST**	**ACTBND**
*Technology Name	Output Commodity	Commodity Cost	Commodity availability
*Unit		M$/mhs	Mhs
MINTTB	TIME	0.00001	13712
MINTTI1	TIME	1.00	100
MINTTI2	TIME	2.00	100
MINTTI3	TIME	3.00	100
MINTTI4	TIME	4.00	100

Figure 7 – Mining processes

			~FI_T								
TechName	**Comm-IN**	**Comm-IN-A**	**Comm-OUT**	**Input**	**Stock**	**CAP2ACT**	**EFF**	**AFA**	**ACTFLO~DEMO**	**FIXOM**	**Life**
*Technology Name	Input Commodity	Auxiliary Input	Output Commodity	Time consumption	Existing Capacity	Capacity to Activity Factor	Process Efficiency	Annual Availability Factor	N. Pass/Mode	Fixed O&M Cost	Lifetime
*Unit				Mhs/MVM	000 Units		MVM/PJ	Max miles per vehicle per year	Pass/Vehicle	M$/'000 Vehicles	
TCARS1	TRAOIL		TSDD		15841	0.001	302	12302	1.67	0.16	8
		TIME		0.052							
TCARL1	TRAOIL		TLDD		15841	0.001	378	2664	1.67		8
		TIME		0.045							
TBUSS1	TRAOIL		TSDD		21.35	0.001	103	37523	9	4.73	20
		TIME		0.616							
TBUSL1	TRAOIL		TLDD		1.41	0.001	112	37523	9	4.73	40
		TIME		0.588							
TTRAINS1	TRAOIL		TSDD		0.00	0.001	9	77732	102.6	100	40
		TIME		-							
TTRAINL1	TRAELC		TLDD		0.11	0.001	7	77732	102.6	100	40
		TIME		4.154							
TPLANEL1	TRAOIL		TLDD		0.00	0.001	5	100000	100	400	40
		TIME		-							

Figure 8 – DMD processes implementation

The DMD technologies implementation is shown in Figure 8**Error! Reference source not found.**. For buses, trains and planes it is a standard VEDA-TIMES description with technology name, description, commodity input, auxiliary input to include the TIME commodity in the analysis, commodity output and some parameters for each technology (stock, efficiency, life, etc.).

For cars, as said before we used a trick to implement different TIME input for short and long distance demand. The trick is to include in the model two different cars technology but use the two technology as a single real car. The two technologies are represented with the same Stock, Cap2Act, ActFlo and Life but with different Input for the COMM-IN-A (auxiliary TIME input), EFF, AFA and FIXOM.

The new technologies are in the SubRes workbook and are described in the same way as the existing technologies, except for the Start parameter, as shown in Figure 9.

			~FI_T									
TechName	Comm-IN	Comm-IN-A	Comm-OUT	START	Input	CAP2ACT	EFF	AFA	ACTFLO ~DEMO	INVCOST	FIXOM	Life
*Technology Name	Input Commodity	Auxiliary Input	Output Commodity		Time consumption	Capacity to Activity Factor	Process Efficiency	Annual Availability Factor	N. Pass/Mode	Investment Cost	Fixed O&M Cost	Lifetime
*Unit					Mhs/MVM		MVM/PJ	Max miles per year	Pass/Vehicle	CUR/000_Vehicles	M$/'000 Vehicles	
TCARS2	TRAOIL		TSDD	2009		0.001	302	11493	1.67	23.55	0.16	15
		TIME			0.052							
TCARL2	TRAOIL		TLDD	2009		0.001	378	2069	1.67			15
		TIME			0.045							
TBUSS2	TRAOIL		TSDD	2009		0.001	103	37523	9	230	4.73	25
		TIME			0.616							
TBUSL2	TRAOIL		TLDD	2009		0.001	112	37523	9	230	4.73	25
		TIME			0.588							
TTRAINS2	TRAOIL		TSDD	2100		0.001	9	77732	102.6	5000	100	40
		TIME			-							
TTRAINL2	TRAELC		TLDD	2009		0.001	7	77732	102.6	5000	100	40
		TIME			4.154							
TPLANEL2	TRAOIL		TLDD	2100		0.001	5	100000	100	20000	400	15
		TIME			-							

Figure 9 – New DMD processes

In this case the new capacity for the cars technologies is controlled via a User Constraints built in a scenario file. This user constraint (Figure 10) is forcing the model to install the same capacity for TCARS2 and TCARL2.

		~UC_T				
UC_N	Pset_PN	Year	UC_NCAP	UC_RHSRTS~FX	UC_RHSRTS~FX~0	UC_Desc
UC_CAR_NCAP	TCARS2	2009	1	0	5	Sum TCARS2 and TCARL2
	TCARL2		-1			

Figure 10 – User constraint to force the same short and long distance car capacity

Expert feedback:

- The model could be simplified by introducing the auxiliary input as a function of the output. In this way will be possible to use two different TIME input depending on the output commodity. Any suggestion about this possibility is welcome.

3 Case studies: California and Ireland

3.1 California data sources

Passenger cars are predominantly used as the preferred mode of transport in California. Public transit, that includes all the commuter trains and buses in the state, comprises about 10% of the total demand (California Dept. of Transportation 2002). The passenger miles travelled (PMT) in the state for all the modes are split between long distance and short distance demands. The short distance demands are captured from the trips within the metropolitan areas in the state, with population greater than 1 million. Table 1 lists the data sources for the attributes used in this model.

Attributes	**Source**
Person trips by mode and average trip distances per person in each region in CA	2009 National Household Travel Survey, 2010 California Household Travel Survey
Travel time for public transit (including waiting time and transfer time)	National Highway Institute of Federal Highway Administration, U.S. Bureau of Transportation Statistics
California population estimates	U.S. Census Bureau
Load factors and availability factors for transit modes	National Transit Database of Federal Transit Administration

Table 1: Data Sources for the California Modal Share model

3.2 Ireland data sources

The characterisation of Irish travel demand according to passenger travel (as opposed to vehicle travel) is not available, therefore this exercise required original research.

For the Irish model, short distance travel demand is defined to be trips of 30 kilometres or less. Total annual travel demand and the base-year modal split of demand by car, bus and train for short and long demand were derived from microdata from Ireland’s Central Statistics Office Pilot National Travel Survey (CSO 2011) conducted in 2009. This used a travel diary methodology to survey travel characteristics, including distance, mode, time and trip purpose, for a cross section of the population. Total annual travel demand in passenger kilometres travelled (PKT) for this modelling exercise was calculated using the average daily distance (by car, bus or train) per person for this survey. The speed of each mode for long and short distance demand was calculated as the weighted average quotient of trip distance and trip time.

In order to calculate load factors for cars and buses, vehicle kilometres travelled (VKT) were used: Total private car VKT for 2008 was derived from national car test odometer readings (Daly and Ó Gallachóir 2011); bus VKT were sourced from the Central Statistics Office (CSO 2008). VKT for Dublin’s light rail system (Dart and Luas) was used for short distance demand.

The characteristics of transport technologies was taken from the Irish TIMES model (Ó Gallachóir, Chiodi et al. 2012).

3.3 Comparing California and Ireland

Figures 11-14 compare the input data and travel characteristics for long and short distance travel for the Ireland and California models.

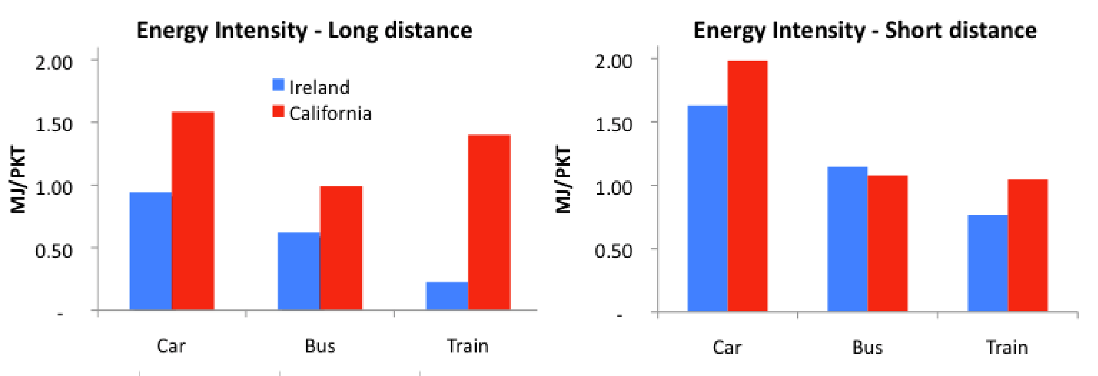

Figure 11: Energy intensity (MJ/PKT)

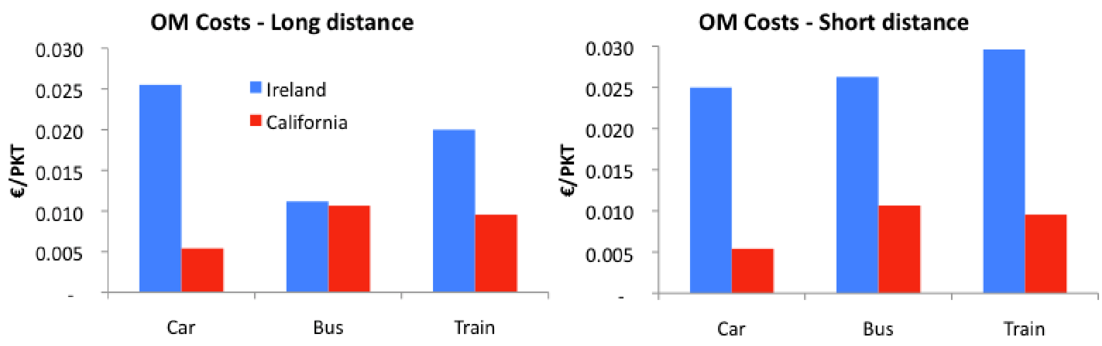

Figure 12: Operation and Maintenance (O&M) costs in €/PKT

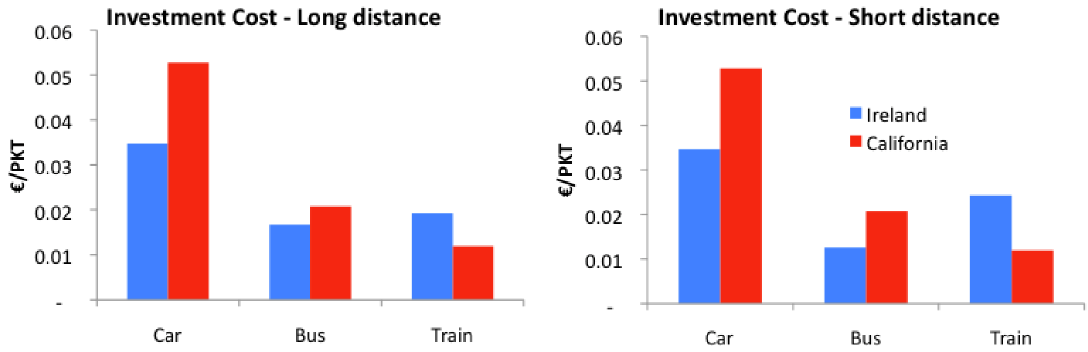

Figure 13: Investment costs (€/PKT)

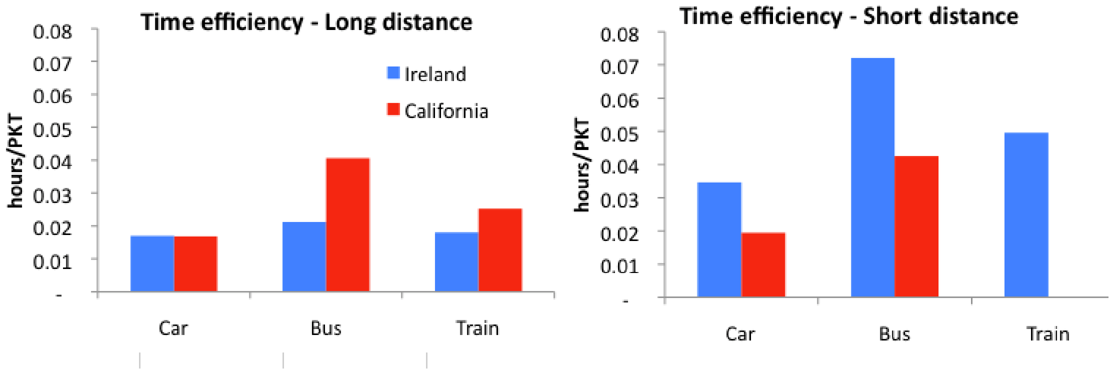

Figure 14: Times efficiency (inverse of travel speed) in hours/PKT

4 Results

The modal-share model is run for several scenarios for each region. Table 2 gives the descriptions of all the scenarios of this modelling exercise.

Scenarios	**Description**
No TTB limit	This scenario imposes no TTB constraint. Allows competition between modes based on technology and fuel costs only.
Reference case	This scenario uses constant TTB per capita over the time horizon. Competition between modes is based on time in addition to cost.
Introducing TTI	Different levels of TTI are modelled as a proxy for investments to reduce travel time.
CO_2 constraint	This scenario includes a 20% CO_2 emissions reduction by 2020 to the above scenarios.

Table 2: Description of scenarios in the modal-share model

4.1 No limit on Travel Time Budget:

This scenario represents the outcome of standard TIMES model structure. The model is first run without the limit on travel time budget, which implies the passenger has no bound on travel time. The model chooses freely between modes on the basis of technology and fuel costs. As shown in the Figure 15, once the existing car capacity retires, the model chooses new bus technology for both regions, which is the slower and cheaper mode of transport according to our assumptions.

4.2 Reference Case:

A constant travel time budget is introduced into the model based on the annual passenger miles travelled (PMT) and passenger kilometres travelled (PKT) data. Population is assumed to grow by 3% annually, and, using a fixed travel time budget (TTB), total travel time for the model also grows by 3% per year. It’s assumed that the distance travelled per person grows by 1% annually, therefore pushing the model to choose faster modes of travel within the given time budget. Results for this scenario are shown in Figure 15. For both models, the model quickly becomes unfeasible if travel demand grows faster than the TTB constraint, as private cars (the fastest mode) are already saturating travel demand, and the model has no faster mode to switch to.

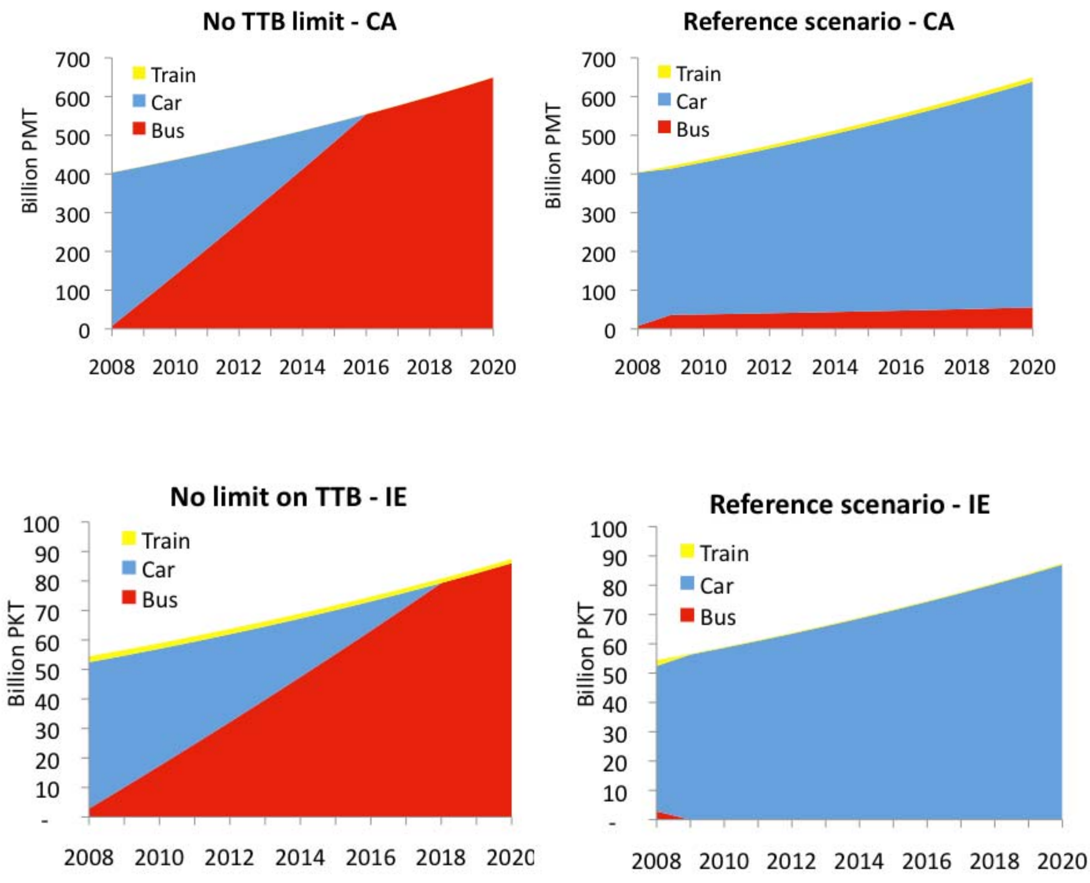

Figure 15: Total transport demand by mode without limit on TTB vs. reference case

4.3 Introducing TTI:

Travel Time Investment (TTI) is introduced in this scenario, allowing the model to invest in increasing the overall travel time budget. This variable acts as a proxy for the investment required to encourage modal shifting, for example through improving public transport speeds. The cost of TTI impacts significantly on results: Figure 16 shows results for “High cost” and “low cost” TTI . For each region, with a low TTI price the model favors a high level of public transport, as the price associated with investments to reduce travel time (modelled as the extra travel time) is small compared with switching to the faster mode of transportation (i.e. private cars). At low TTI cost, the model for both regions also chooses a level of rail transport, which has a higher cost but greater speed than bus transport. When TTI cost is sufficiently high, the model invests in new private cars exclusively in Ireland, and invests in some new bus technology in California as well as private cars. At very high TTI costs, the model chooses exclusively private cars in meeting travel demands, and the current capacity of bus and rail isn't used.

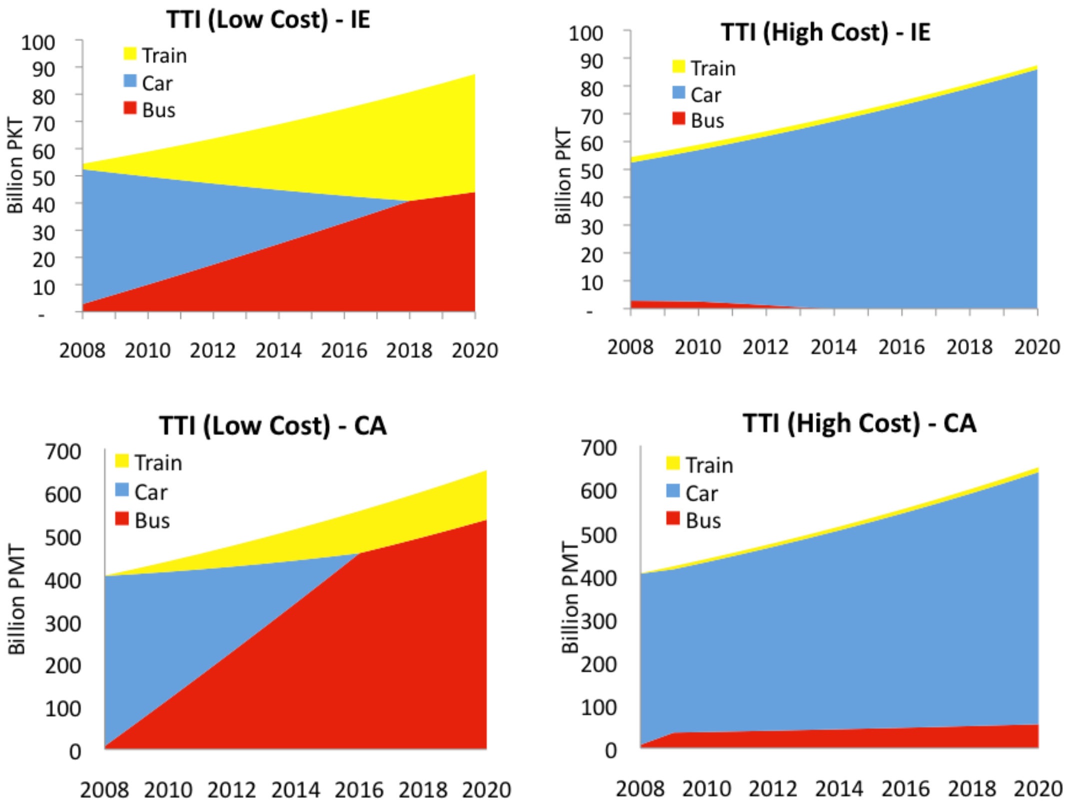

Figure 16: Total travel demand by mode under different TTI investment scenarios, for low and high price investment

4.4 Carbon Emissions Constraint:

This scenario introduces a 20% CO_2 emissions reduction constraint is applied to the TTI (High Cost) scenario described above. In the emissions constraint scenarios, the model chooses public transport at a higher rate than the scenarios without the emissions constraint, illustrated in Figure 18.

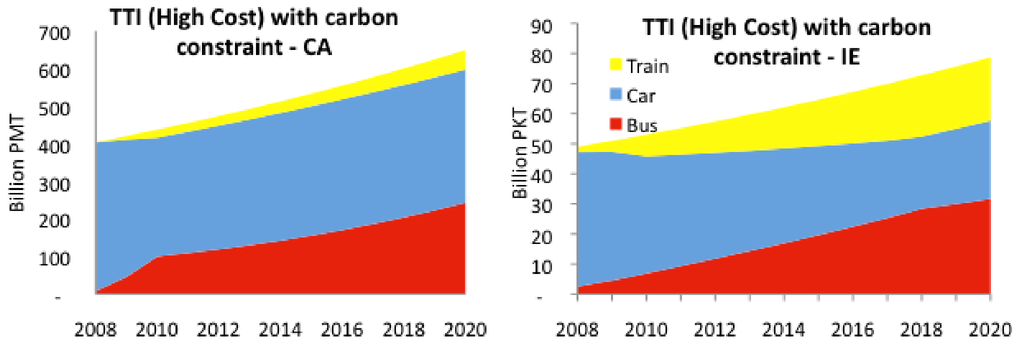

Figure 17: Travel demand in a high cost TTI investment scenario with a 20% carbon constraint

5 Discussion

5.1 Travel Time approach

Schafer (2012) has highlighted the importance of modifying travel behaviour in reducing global greenhouse gas emissions, and the key challenge of representing this role in technology models. The approach taken here addresses this modelling gap by endogenising competition between modes using the concept of a travel time budget in a cost-optimising linear model.

Applying the approach to two regions firstly highlights the differences in travel demand between Ireland and California, and secondly shows that depending on data sources, different approaches to the model and data may be taken. For example, with regard to the definition of long and short distance travel demand, data for Ireland is not geographically detailed and therefore short distance travel is based on trip length, whereas for California, travel demand is characterised by metropolitan/suburban trips.

Our model uses a highly stylized TTI variable to represent investment potentials to reduce travel time through investments in public infrastructure, such as more bus/rail routes. We do so by relaxing the TTB constraint with new investments in TTI and the model results appear to be sensitive to this variable. Thus, the important next step is the calibration of the Travel Time Investment variable. The cost of TTI is critical to the choice of modes: At low TTI costs, the model only favors low-cost public transport, which is an unrealistic result. The TTI cost must be calibrated for the region in question to ensure the results are reflect a realistic baseline. In a carbon constrained scenario, the cost of mitigation depends on TTI cost, so in a full TIMES model, the level of modal shifting would depend on the TTI cost, speed of technologies and the relative costs of other carbon mitigation technologies.

A physical interpretation of this variable is the cost to policymakers of achieving a shift towards less carbon intensive modes. Future refinements of this model could use a cost curve to reflect different programmes at different costs.

5.2 Other transport modelling techniques

As part of this research, the use of standard transport modelling techniques was investigated. Logit models are commonly used in transport studies to model the relationship between the choice of travel mode (among other travel decisions) and some variables which could effect this choice, such as household structure, income, or the quality of public transport. This method is a simulation, not optimisation, model and involves non-linear probability functions. The use of logit modelling was investigated and deemed unlikely to be compatible with the linear optimisation approach of TIMES.

Another way of modelling mode choice shift is to utilize cross price elasticity between different modes: cars, buses, rail, etc. The cross-price elasticity describes the changes in the demand of one mode when the price of the other mode increases. This method requires estimates of both own-price elasticity (which is already available in the TIMES model) and mode choice elasticity. So, for example, when gasoline price increase, consumers can either reduce driving, or switch to bus transit, or both. This implementation, however, will require code changes to the TIMES model and is therefore a long-term solution. The cross-price elasticity can also be used to calibrate the TTI variable developed in this paper in future studies.

5.3 Conclusion & future steps

The modal shift modelling methodology, implemented in a simple TIMES model presented here, is a significant and novel step towards incorporating behaviour into energy systems models.

At present, the TTI variable is a proxy for the cost of investment that increases the speed of modes. This variable needs further study in the context of a full energy system model. The representation of technology in the model is currently limited, with four technologies and two fuels. Future possibilities for this research are to expand the model to include a full range of transport technologies in order to investigate the trade offs between modal shifting and investment into alternatively fuelled vehicles under a range of scenarios, to endogenise the relationship between investment in infrastructure and reduced travel time, to incorporate elasticities with regard to demand and to investigate the inclusion of cross-price elasticities into the TIMES code.

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